The Effect of Ambiguous Stimuli on the Error Signal in ERP

by

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Abstract

The error-related negativity (ERN) is a component of event-related brain potential (ERP) that is expressed when human subjects make errors on certain response tasks. The present study focuses on the impact of perceptual ambiguities on the brain's error signal, as indicated by the amplitude of the ERN waveform. It is concerned with whether ambiguous stimuli yield a larger or smaller error signal in the ERP than do non-ambiguous stimuli; previous studies have compiled evidence for both scenarios. We hypothesized that error signals associated with non-ambiguous stimuli would be greater due to a larger mismatch between correct and actual response representations in the brain. To test this hypothesis, behavioral and EEG data were collected as participants performed a simple choice reaction time task. The results found no significant effect of stimulus ambiguity on ERN amplitude, but revealed a trend in the direction of our hypothesis.

The Effect of Ambiguous Stimuli on the Error Signal in ERP

The ability to accurately monitor one's behavior is essential in order to perform many everyday tasks. Our capacity to learn new skills, avoid adverse scenarios, and behave properly in an array of settings hinges on this ability. While it might seem like a complicated process, the evaluation of behavioral outcomes may begin with a simple brain signal indicating whether a performed action was good or bad. This study serves to investigate the properties of this brain signal elicited upon error commission in a choice reaction time task involving ambiguous and non-ambiguous stimuli.

Introduction to the ERN

The introduction of electroencephalography technology has provided an accurate and reliable means of examining brain activity. Decipherable event-related potential (ERP) components within human electroencephalogram (EEG) readings are thought to reflect the activation of neural mechanisms evoked by a variety of mental processes. One particular ERP component of interest is the error-related negativity (ERN). The ERN appears as a negative deflection in the response-locked ERP that most commonly occurs when people make errors in reaction time tasks (Falkenstein, Hohnsbein, Hoorman, & Blanke, 1990, 1991; Gehring, Coles, Meyer, & Donchin, 1995; Gehring, Goss, Coles, Meyer, & Donchin, 1993). Figure 1 shows the original ERN waveforms reported in Falkenstein et. al. (1991) and Gehring et. al. (1993). The onset of the ERN occurs shortly before an erroneous button press and peaks approximately 100 ms after response onset (Bernstein, Scheffers & Coles, 1995). Readings are most robust at midline frontocentral locations, site FCz in particular.

Further studies utilizing source localization suggested that the region underlying the generation of the ERN was the anterior cingulate cortex, or the ACC (Dehaene, Posner &

Tucker, 1994; Holroyd, Dien & Coles, 1998; Miltner, Braun & Coles, 1997). Figure 2 provides a diagram pinpointing ACC activation during conflict. This discovery heightened interest in the ERN due to the ACC's posited role in *cognitive control* – processes that enable the brain to adapt behavior to changing task demands and environmental circumstances (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). These series of processes are considered essential to successful behavior. Cognitive control includes processes that detect when control is needed as well as those that implement control through changes in attentional focus and processing priorities as well as through other strategic adjustments (Miller & Cohen, 2001). Because an error is a prominent marker of performance breakdown, and error commission triggers the ERN, the ERN is thought to demonstrate a process associated with evaluating the need for and/or implementing control. The greater implications of the ERN have attracted enough attention to lead to the development of several fascinating, competing theories.

Competing Theories of the ERN

Early theories of the ERN proposed that it acted as a marker involved in error detection and compensation. Coming to be known as the error detection or comparator theory, it suggested that the ERN reflects a process that compares the output of the motor system (essentially an efferent copy of the response movement) to the best estimate of the correct response at the time of ERN occurrence (Falkenstein et al., 1991; Gehring et al., 1993). At the center of this process is a *comparator*. The short duration of the ERN coupled with its temporal proximity with the response suggest that the ERN is initiated upon the arrival of the efference copy of the response movement at the comparator (Coles, Scheffers, & Holroyd, 2001). This theory proposes that the ACC might act as a comparator, as first proposed by motor physiologist Vernon Brooks (Brooks, 1986). Figure 3 shows a slightly modified schematic diagram of this theory as published by

Coles et al. (2001). In almost all cases Coles et al. investigated, errors on speeded response tasks were most likely to be due to fast guessing or other forms of impulsive responding. The theory posits that stimulus evaluation is not complete when the response is executed, which leads to an incorrect representation of the stimulus. The comparison system does not wait until all possible information regarding the appropriate response is evaluated. Further, continued processing of the stimulus yields a second, correct representation beyond that used to guide the actual response. The comparator then computes the difference between these two representations. A disagreement between these representations gives rise to a mismatch, as manifested by an error signal.

Researchers have proposed several ways in which the ERN could be generated from within this system. Coles et al. (2001) and Falkenstein et al. (1990) believe the ERN expresses the output of the comparison process. They claim it is generated by the arrival of the error signal at the second error-processing component, the remedial action system. Another possibility, as proposed by Gehring et al. (1993) and supported by Holroyd and Coles (2002), is that the ERN reflects a process that uses information in the error signal to inhibit the error or to correct it. It may also use the information to make certain strategic adjustments, such as attentional focus or response bias, that reduce the likelihood of errors re-occurring in the future. Yet another view suggests it is the actual mismatch between the anticipated and actual stimuli that generates the ERN, weighing more heavily on stimulus representations (Bernstein et al., 1995; Schmidt & Gordon, 1977). The error-detection theory will be discussed further in following sections, as it is most relevant to the current study.

A second dominant theory of the ERN is the conflict monitoring theory. As originally proposed by Carter, Braver, Barch, Botvinick, Noll, and Cohen (1998) and Botvinick et al. (2001), the ERN reflects the degree of conflict inherent in performing a task rather than signifying the actual commission of an error. Initially emerging as an alternative to the error detection theory, it argued that error detection was computationally improbable (Botvinick et al., 2001; Carter et al., 1998; Yeung, Botvinick, & Cohen, 2004). The logic behind their argument rested on the idea that the comparator, in order to choose the correct representation, must have information that specifies which of the representations being compared is the correct one. If the comparator already has this information available, it must be receiving it from a source outside the processes responsible for the current task; the system generating the ERN would have to know the intended (correct) action (Carter et al., 1998). Supposing this is the case, why isn't the comparator executing the correct response if it already knows which one is correct?

The conflict model introduces response conflict as the solution to this problem. Response conflict is defined as concurrent activation of multiple competing resources (Botvinick et al., 2001; Yeung et al., 2004). These competing resources encompass the same two actual and correct responses discussed in the error-detection theory. Upon activation of both these representations, response conflict can track performance accuracy without the system ever knowing which representation is correct. They argue response conflict is quantifiable, and the amount of response conflict impacts the size of the ERN. Upon committing an error, both an incorrect channel and slightly delayed correct channel will be activated, and the product of these two channels reflects the amount of response conflict (Yeung et al., 2004). Heightened conflict would therefore detect a need for increased control in situations where errors are more likely, improving future performance by strengthening the task set. According to the model, a stimulus is processed and information is then sent to the ACC. Upon receipt of this information, the ACC elicits the ERN if there is ample conflict between the actual output and the representation of the correct response. This information is then looped back into the processing of the next stimulus to facilitate further performance. The theory predicts, because the conflict monitoring system can drive changes in response strategy (Botvinick et al., 2001), that the ERN may represent a process that reallocates control among various motor controllers, suggesting the size of the ERN will be associated with changes in response strategy (Holroyd, Praamstra, Plat, & Coles, 2002). This prediction is consistent with Gehring et al.'s (1993) original study, which found evidence that the ERN is sensitive to an emphasis of speed or accuracy in responding. This concept will be discussed further in a later section.

One of the more recent theories to emerge has been coined the reinforcement-learning theory of the ERN, or RL-ERN. Slightly more comprehensive than previous theories and including a computational aspect, the RL-ERN starts with a monitoring system in the basal ganglia that produces an error signal when an untoward event occurs (Holroyd et al., 2002). This information then activates the mesencephalic dopamine system, which conveys the error signal to the ACC where it is used to adjust task performance. An efferent copy of the planned response is then fed back to the basal ganglia to allow for the prediction of future behavior. If the response doesn't result in optimal outcomes, a signal is sent to the ACC to disinhibit control in the motor system so that a new plan can be generated. This process ultimately reinforces learning in the task at hand and thereby reduces error commission in successive trials.

According to this model, the ACC elicits the ERN upon receipt of information sent via the mesencephalic dopamine system. Similar to the conflict monitoring theory, the RL-ERN says the ERN represents a process that reallocates control among various motor controllers, rendering it sensitive to changes in response strategy and technique.

An important feature of this model is the prompt response of the monitoring system to the earliest indication that something has gone wrong. At this time, early errors occur because the system does not yet have a representation of the contingencies among stimuli and responses, and therefore must rely on external feedback to judge performance. After performing the task several times, associations are learned between rewards and stimulus-response pairings and the system no longer needs to rely on external feedback to detect errors. Errors can now be detected immediately when the response occurs (Holroyd et al., 2002).

Error-Correct Mismatch

A mismatch between information related to the correct response and information related to the erroneous response/error in a task is central to all major theories of the ERN. According to the error-detection theory, the ERN is elicited by a comparison between mismatching information regarding the actual, erroneous response and information regarding the correct response. Conflict monitoring theory accounts suggest the ERN is discharged by temporally overlapping mismatched activations of the correct and incorrect response (response conflict) on error trials. Finally, the RL-ERN theory suggests the ERN reflects the mismatched comparison of the values of correct and incorrect stimulus-response conjunctions (Gehring et al., 2008).

Beyond all the major theories encompassing error-correct mismatch, they all make the same prediction regarding the ERN: its amplitude should be sensitive to the amount of mismatch. Many studies have set out to investigate this paradigm, some consistent with a mismatch account and others finding no correlation. Bernstein et al. (1995) and Falkenstein, Hohnsbein, and Hoormann (1996) confirmed expected results of increased ERN amplitudes as error and correct representation grew more dissimilar, while Gehring and Fencsik (2001) showed just the opposite, reporting greater ERN amplitudes for errors involving representations more similar to the response (more similar to each other). Attempting to explore these conflicting results further, Elton, Spaan, and Ridderinkhof (2004) reported that stimulus mismatch failed to affect the ERN amplitude in an experiment utilizing an auditory stimulus discrimination task. Despite their reported results, their data indicate a significantly larger ERN amplitude at site Cz for errors with large stimulus deviation compared to small-deviation errors (Gehring et al., 2008). Taking the concept of mismatch in a different direction than previous studies, Yeung, Ralph, and Nieuwenhuis (2007) demonstrated that merely increasing the brightness of the stimuli increased the amplitude of the ERN. The concept of mismatch behind this study claims that brighter stimuli are more salient than dimmer stimuli, therefore resulting in mismatching stimulus information that alters the ERN.

Taken together, studies regarding error-correct mismatch and the ERN are inconclusive. Contradictory evidence has been presented by several sources and a wide range of tasks and stimulus manipulations make a direct evaluation of error-correct mismatch difficult. However, existing evidence indicates some variant of mismatch most likely impacts the ERN and is worthy of further experimentation.

Present Study

Based on our review of the ERN literature, we have identified the need for a straightforward examination of the effect of mismatch on ERN amplitude. Arguably the most important unresolved issue surrounding mismatch is that of stimulus similarity. Schmidt and Gordon (1977) conducted the first study bridging these two issues, hypothesizing that mismatch could involve the stimulus predicted by the error response and the stimulus that actually occurs. Since then, several studies have set out to examine the effects of different stimuli on the ERN. Bernstein et al. (1995) reported that while stimulus similarity did not affect the ERN significantly, the direction of the effect indicated that more dissimilar stimuli yielded a larger ERN than similar stimuli. However, this study used slightly controversial methods as it also aimed to investigate numerous other conditions, possibly allowing for a confounding effect. Additionally, the study did not present any waveforms, necessitating further research on the issue.

More recently, Elton et al. also found that stimulus mismatch did not affect the ERN in the realm of auditory stimuli. They employed three different levels of pitch similarity and reported that ERN amplitudes on none of the levels were significantly different. However, upon further investigation of their data, a significant interaction with electrode site is seen (see Gehring et al., 2008 for a discussion). The ERN amplitude at site Cz was significantly greater for errors with large stimulus deviations (dissimilar pitches) as opposed to small deviations (similar pitches). A clear relationship between stimulus similarity and ERN amplitude cannot be extracted from this study, but evidence again points to a potential correlation warranting further investigation.

The present study serves to clarify the conflicting evidence provided by several studies involving stimulus similarity and the ERN amplitude. It employs a basic stimulus discrimination task involving two levels: ambiguous and non-ambiguous. The simplicity of the design is intended to yield clear results as to whether or not stimulus similarity impacts the ERN amplitude, and if so, in what direction. In accordance with the error-detection theory, we hypothesize that more dissimilar (non-ambiguous) stimuli will produce a greater ERN relative to similar (ambiguous) stimuli due to a greater mismatch between correct and actual (incorrect) representations of the stimulus.

Method

Participants

Sixteen undergraduates participated in an electroencephalography (EEG) experiment that required them to distinguish between ambiguous and non-ambiguous stimuli viewed from a computer monitor. The study consisted of 9 male and 7 female undergraduate students at the University of Michigan. Twelve of these subjects participated in partial fulfillment of psychology/communications course requirements, and four participated out of interest in the study (2 male and 2 female). Six of the sixteen participants were excluded from analyses due to unsatisfactory/contaminated data or equipment malfunction while collecting the data. Subjects ranged from ages 18-22 with a mean age of 19.4. All were right-handed with normal or corrected-to-normal vision.

Stimuli

Participants completed a choice reaction time task for two levels of stimulus discriminability. In the high stimulus feature overlap condition (HO), participants chose between the letters E and F, while in the low stimulus feature overlap condition (LO) they chose between X and O. Stimuli appeared on a 15-inch computer monitor of resolution 1024x760 in size 24 Helvetica font. A stimulus (single letter) was flashed at the center of the screen for 100 ms followed by a fixation cross (+) lasting a duration of 1500 ms, after which another stimulus was flashed. For the HO condition, the subject was instructed to press the left button on a response pad if they viewed an E and the right button if they viewed an F. For the LO condition, X was left and O was right. Data were collected in a sound-attenuated and electrically shielded room.

The experiment was composed of five blocks of one-hundred trials for the HO condition and five blocks of one-hundred trials for the LO condition. Within each block the stimuli were presented in random order with an equal probability of either letter being chosen. The order of the blocks were counterbalanced so that half the subjects performed the HO condition first and the other half performed the LO condition. Participants were given verbal feedback half way through the experiment and told to go faster, slower, or remain at a similar pace in order to achieve an error rate of approximately 10%. Accuracy and reaction times were collected for each subject.

Procedure

The participants were greeted by the experimenter and explained that they would be performing an EEG experiment before being given an informed consent form. Once completed, the participants were seated while the experimenter applied four face electrodes and an additional electrode on each mastoid. Their head circumference was measured and they were fitted with an electrode cap accordingly. Electrolyte gel was then applied to each of the 64 electrode housings before the electrodes were inserted. All wires were neatly wrapped behind the participant's head and they were moved into the experiment booth containing a computer screen and response pad. The electrodes were plugged into the receiver and checked for offsets exceeding 40 kOhm. Extra gel was added to electrode housings showing bad readings until corrected. Once all equipment was tested and working properly, the experimenter explained the task to the subject.

Upon completion of the task, equipment was removed and participants were given an opportunity to wash any extra gel out of their hair using shampoo and towels supplied by the experimenter. They were then debriefed, thanked for their participation, and given a debriefing form that further explained the purpose of the study.

Electrophysiological Recording and Analysis

The EEG was recorded with Ag/AgCl electrodes embedded in a nylon cap at 64 scalp locations. The data were referenced off-line to bipolar mastoid electrodes. Electrooculogram

(EOG) was recorded from electrodes placed above and below the left eye and on the outer canthi of both eyes. EEG and EOG data were collected using an ActiveTwo system (BioSemi Inc., Amsterdam, the Netherlands) and oculomotor movements were corrected using the procedure found in Gratton, Coles and Donchin (1983). Trials containing movement artifact, drift, or any other impurities were excluded. Stimulus- and response-locked epochs were then extracted for both error and correct trials and averaged for each participant prior to quantification of the ERN component.

The ERN was measured in response-locked waveforms as the base-to-peak voltage difference between the most negative peak occurring 0-100 ms post-response and the most positive peak occurring -50 to 50 ms around the response. This measure was calculated for both error and correct trials, separately for E/F and X/O block types. The statistical analyses relied on data from electrode sites yielding the largest ERN amplitudes: Fz, FCz, and Cz.

Results

Behavioral Results

We first examine reaction time (RT) and accuracy for the task as a whole before assessing any EEG results. Error rates were computed for each block type (E/F = 7%; X/O = 5%) and a two-sample t-test was implemented. The results indicated no significant difference ($t(9) = 0.88$, $p = .20$), giving evidence of consistent accuracy between blocks. Figure 4 shows a graphical representation of error rates for each block type.

We predicted that block type E/F would yield greater reaction times in correct trials due to greater stimulus ambiguity, but that reaction times would be similar for both blocks in error trials. A 2 (block type: E/F, X/O) x 2 (accuracy: correct, error) repeated measures ANOVA was run using RT data. Output revealed a significant main effect of accuracy ($F(1,9) = 21.557$, $p <$

.01, *MSE* = 1046.667), indicating a difference in RT for correct vs. error trials. However, RTs for E/F vs. X/O blocks proved similar as there was no significant main effect for block type ($F(1,9) = 3.1$, $p = 0.112$, *MSE* = 614.344) despite a significant interaction between block type and accuracy ($F(1,1) = 5.396$, $p < .05$, *MSE* = 373.678). Figure 5 visually confirms our earlier prediction, showing the relationship between accuracy and RT for both block types.

Paired samples t-tests were conducted between and across both block type and accuracy. As expected, a significant difference was discovered for accuracy within blocks for both block types (E/F: $t(9) = -4.636$, $p = .001$; X/O: $t(9) = -3.220$, $p = .01$). A reliable difference of RT was also seen between block types for correct trials ($t(9) = 4.270$, $p = .002$), but not for error trials ($t(9) = -.032$, $p = .975$). These results statistically confirm the visual relationship implied in figure 5, further substantiating our prediction. Additionally, figure 6 displays a graphical representation of RTs for correct and incorrect trials broken down by block type.

ERN Results

Grand-averaged response-locked waveforms from electrodes Fz, FCz, Cz, and Pz are plotted in figure 7. Negative μV are plotted upward. The ERN is clearly evident as a negative peak in error trials occurring approximately at response onset (0). Channel data for electrode Pz was excluded from statistical analyses due to the lack of a robust ERN waveform. ERN amplitude data was input into a 3 (channel) x 2 (block) x 2 (accuracy) repeated measures ANOVA. Similar to the behavioral results, a significant main effect of response accuracy on ERN amplitude was evident, $F(1,9) = 26.470$, $p < 0.001$, *MSE* = 14.133, indicating an ERN is present on error trials, but the difference in ERN amplitude was not significant by block type $F(1,9) = 1.515$, $p = 0.250$, *MSE* = 7.497. Figure 8 demonstrates that the trend of ERN amplitude by block type was larger for X/O trials relative to E/F trials at each electrode site. Planned comparisons tests revealed no significant ERN amplitude difference between block type for any of the three electrode sites, Fz: $t(9) = 0.967$, $p = .359$; FCz: $t(9) = 1.296$, $p = 0.227$; Cz: $t(9) = 1.527$, $p = 0.161$. Further planned comparisons between correct and error waveforms at all three electrode sites were performed to test for the presence of the ERN. These tests revealed a significant ERN for both E/F and X/O blocks at all 3 electrode sites, Fz: EF, $t(9) = 2.787$, $p < 0.05$; XO, $t(9) = 4.765$, $p < 0.001$; FCz: EF, $t(9) = 3.784$, $p < 0.005$; XO, $t(9) = 5.097$, $p < 0.001$; Cz: EF, $t(9) = 3.564$, $p < 0.01$; Cz_XO: $t(9) = 2.450$, $p < 0.05$.

Upon examining the waveforms, it became apparent that correct trials exhibited an ERN-like waveform of a lesser amplitude. Previous studies have found similar phenomenon. No statistical analyses were run on these waveforms outside of those already performed, but their presence on significant trials may reflect greater uncertainty during stimulus and response processing and will be discussed in the following section.

Discussion

This experiment sought to examine the effects of stimulus ambiguity on the ERN component of ERP through a simple choice reaction time task. We hypothesized that ambiguous, or more dissimilar, stimuli would elicit a larger ERN relative to non-ambiguous stimuli due to a greater representational mismatch of correct and actual responses. It is helpful to compare our hypothesis against the predictions of all three competing ERN theories.

While stimulus mismatch is generally associated with the error-detection theory, similar predictions are easily generated by the conflict monitoring theory and the RL-ERN. Recall that because each of these theories relates the ERN to some type of error-correct mismatch, they all predict the ERN should be sensitive to the amount of mismatch. Additionally, all three theories predict that greater amounts of mismatch will be associated with larger ERN amplitude. The aspect that these models differ in is the processes in which the ERN is generated and the types of mismatch that affect it.

The error-detection theory posits that the ERN is, as its name suggests, generated upon detection of an erred response. At the time of detection, the amount of discrepancy between information corresponding to the actual (erroneous) response and the correct response determines the amount of mismatch. This means that stimuli with low feature overlap (X/O) should create a larger mismatch than stimuli with high feature overlap (E/F). According to this theory, ERN amplitudes should be larger for non-ambiguous X/O trials due to a greater amount of response representation mismatch.

Conflict monitoring accounts argue that temporally overlapping activations of correct and incorrect response channels on error trials create a certain level of response conflict, which ultimately determines the amplitude of the ERN. By this account, non-ambiguous X/O trials would correspond to higher-conflict trials, and therefore a larger ERN. However, a study conducted by Orr, Muthusamy, and Gehring (2008) found more behavioral interference for high feature overlap conditions, which might suggest greater conflict on these trials. They postulate that greater response uncertainty may cause heightened response activations, therefore increasing the product of the response channels. By definition, this would increase response conflict and implicate a larger ERN for E/F trials rather than X/O. The theory is applicable to either situation.

Finally, RL-ERN theory suggests that comparisons of the correct and incorrect values of stimulus-response conjunctions are learned, and the ERN is a reflection of the mismatch between these correct and incorrect stimulus-response conjunctions as a whole. This model would predict that the difference between correct and incorrect conjunctions are larger for non-ambiguous X/O trials, and consequently be correlated with a larger mismatch and greater ERN. We find that predictions from all three competing theories align with our hypothesis.

Although an initial examination of the averaged waveforms might allude to a confirmation of our hypothesis, the results indicate no significant effect of stimulus ambiguity on ERN amplitude. Despite insignificant results, all three electrode sites did show a general trend consistent with our hypothesis. That is, ERN amplitudes were larger for non-ambiguous, dissimilar stimuli across all electrode sites (as seen in figure 8). There are several factors that may have contributed to our lack of robust results, one of which may have its roots in the behavioral results.

Reviewing the error rate between the two block types, E/F (ambiguous) and X/O (non-ambiguous), we found no significant difference. This may have been an early indicator that our manipulation of stimulus ambiguity was ineffective. Error commission in this task could occur in two different forms: subjects could either execute a response that is mapped to a stimulus that shares many features with the actual stimulus (e.g., execute F upon presentation of E stimulus), or they could execute a response mapped to a stimulus that has very different features from those of the actual stimulus (e.g., execute X upon presentation of O stimulus). If stimulus ambiguity plays a role in the error-detection process reflected by the ERN, then the ERN should be larger for errors associated with dissimilar, non-ambiguous stimuli (Bernstein et al., 1995). By this thinking, the role of stimulus ambiguity in error generation can be evaluated by looking at our behavioral results for error rate. Subjects should tend to make more errors by executing the response mapped to a stimulus that shares many features with the actual stimulus. Our behavioral results indicate no significant pattern regarding error rate/frequency, possibly rendering the relationship between stimulus ambiguity and ERN invalid. Another possibility is that the error rate for the task was simply too low, failing to generate enough errors to induce a significant difference between the two levels of ambiguity.

Another line of research has found that different response strategies may impact the size of the ERN, thereby possibly influencing the insignificant results discovered between block types. There is a considerable body of evidence supporting a speed/accuracy emphasis effect on error rate and the ERN amplitude. The speed-accuracy tradeoff was initially noted by Pachella (1974) and describes the fact that subjects can respond quickly, making many errors, or slowly, making fewer errors. Many studies have tested this variability, tending to show that a speed emphasis decreases the amplitude of the ERN relative to an accuracy emphasis (Falkenstein et al., 1990; Falkenstein, Hohnsbein, & Hoorman, 1995; Gehring et al., 1993; Ganushchak & Schiller, 2006; Hajcak, McDonald, & Simons, 2003; Ullsperger & Szymanowski, 2004). In this study, different subjects were given different feedback halfway through the experiment that may have emphasized speed or accuracy. Most subjects completed the first half of the experiment above the target accuracy rate of 90% (note mean error rates of 5% and 7% for X/O blocks and E/F blocks, respectively), and were therefore encouraged to respond faster in order to elicit more errors. While counterbalancing the task should control for this effect between blocks, it is possible that a general bias toward speed emphasis may have decreased the overall ERN amplitudes by an amount sufficient enough render the main effect of block type insignificant.

There are several study limitations that may have altered the expected results as well, one of the most obvious being number of participants. This study consisted of 16 subjects with only 10 participants included in data analysis due to time constraints and limited resources, fewer than is standard for ERP experiments. A small number of participants render the data sensitive to additional participants, suggesting another subject or two may have brought the ERN amplitudes to within a significant range. Additionally, a more efficient study design may have given better insight into the relationship between stimulus ambiguity and the ERN. Subjects were only given feedback once throughout the course of the experiment. If their performance was not consistent with that necessary for the task (i.e. not enough errors, not responding quickly enough), half of the subject's data would be inadequate before being given a chance to correct their behavior. The task itself only produced an average error rate of 6%, while the target error rate was 10%. Some subjects may have had too few errors to produce a reliable averaged waveform, thereby skewing the grand-averaged waveform in an undesirable direction. A shortening of stimulus duration might have increased the difficulty of the task and produced a more favorable error rate.

An interesting finding was observed in the waveforms of the correct trials. A negative deflection resembling an ERN of lesser amplitude appeared in the same location as the ERN in error trials. This component has been labeled the correct-response negativity (CRN) due to its occurrence at the same latency in the response-locked waveform as the ERN and has been observed in many studies (Ford, 1999; Gehring & Knight, 2000; Luu, Flaisch, & Tucker, 2000; Scheffers & Coles, 2000; Vidal, Hasbroucq, Grapperon & Bonnet, 2000). Although the amplitude of these waveforms was significantly different than the ERN, the appearance of this component may challenge the idea that the ERN is specifically related to error processing. Coles et al. (2001) set out to dispel the controversy over the ERN not being solely related to error processing, arguing that ERNs may be observed on correct trials due to one or both of two factors: either there is error processing on correct trials, or the response-locked averages used to derive the ERN are contaminated by negative components, such as stimulus-related activity. Inherent in their explanation is the possibility that our observed ERN waveforms were contaminated with stimulus-related components. Future study designs should take stimulus-related activity into account and be sure to separate this component from the ERN to allow for accurate results.

In the end we find that all three well-established theories align with our hypothesis, yet all three accordingly clash with our results. This information combined with a general trend of ERN amplitudes in the direction of our hypothesis dissuades us from ruling out an effect of stimulus ambiguity on ERN amplitude despite insignificant results. It is not obvious that these effects are completely inconsequential and further research implementing a more reliable study design is warranted.

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Figure Captions

Figure 1. Original response-locked ERP waveforms examining errors.

A. Stimulus-locked (STA) and response-locked (RTA) grand average ERP waveforms for correct and error trials evoked during a visual discrimination task with focused attention blocks (FA) and divided attention blocks (DA). This is the first report of a response-locked negative component occurring shortly after the time of the response, and was labeled as the error negativity (Ne). (Modified from source: Falkenstein, M., Hohnsbein, J., Hoorman, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components: II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology, 78*, 447-455.)

B. Response-locked grand average ERP waveforms for correct and error trials evoked during a Flanker paradigm. This is the first report of the ERP component known as the Error-Related Negativity (ERN) (source: Gehring et al., 1993).

Figure 2. A mid-sagittal view of the ACC showing overlapping action for four different forms of conflict: pre-response conflict, decision uncertainty, response error, and negative feedback. The ACC is thought to be the neural mechanism underlying the ERN (source: Ridderinkhof et al., 2004).

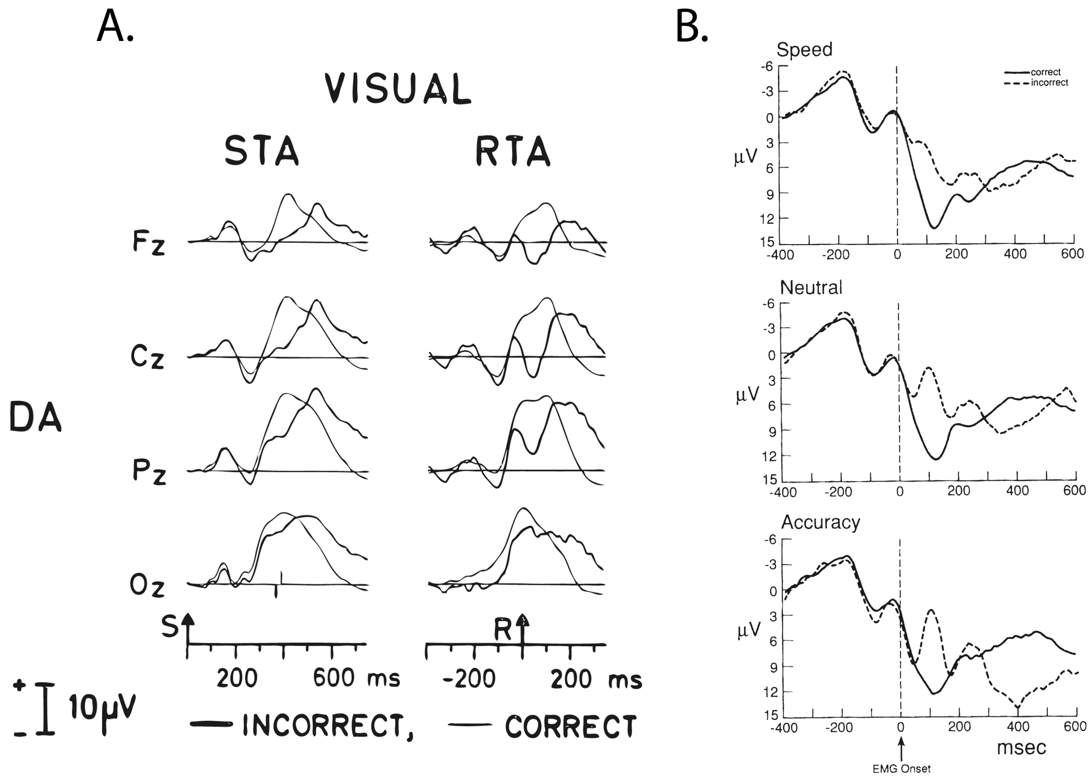
Figure 3. Schematic diagram illustrating the error-detection theory of the ERN, which suggests that a monitoring system compares the difference between the representation of the correct response and the representation of the actual response (due to incomplete, ongoing evaluation of the stimulus). A discrepancy between these two representations gives rise to a mismatch or error signal, which underlies the ERN (source: Coles et al., 2001).

Figure 4. Illustrates the error rates for both block types EF and XO. No significant difference is found.

Figure 5. Reaction times are plotted for each block. Within each block, times are displayed for both error and correct trials. Illustrates a significant difference between block types for correct trials, but no significant difference for error trials.

Figure 6. Grand-averaged ERP waveforms are shown for all 10 participants. Waveforms for EF error, EF correct, XO error, and XO correct trials are given from electrode sites Fz, FCz, Cz, and Pz. The ERN is clearly visible at sites Fz, FCz, and Cz for error trials. Note that apparent differences in ERN amplitude between EF and XO error trials are not significant.

Figure 7. Graph of average ERN amplitude for EF and XO error and correct trials. ERN amplitudes are measured from maximal peak to minimal peak of the waveform, showing averaged results for electrode sites Fz, FCz, and Cz. Note apparent differences are not statistically significant, but display a general trend.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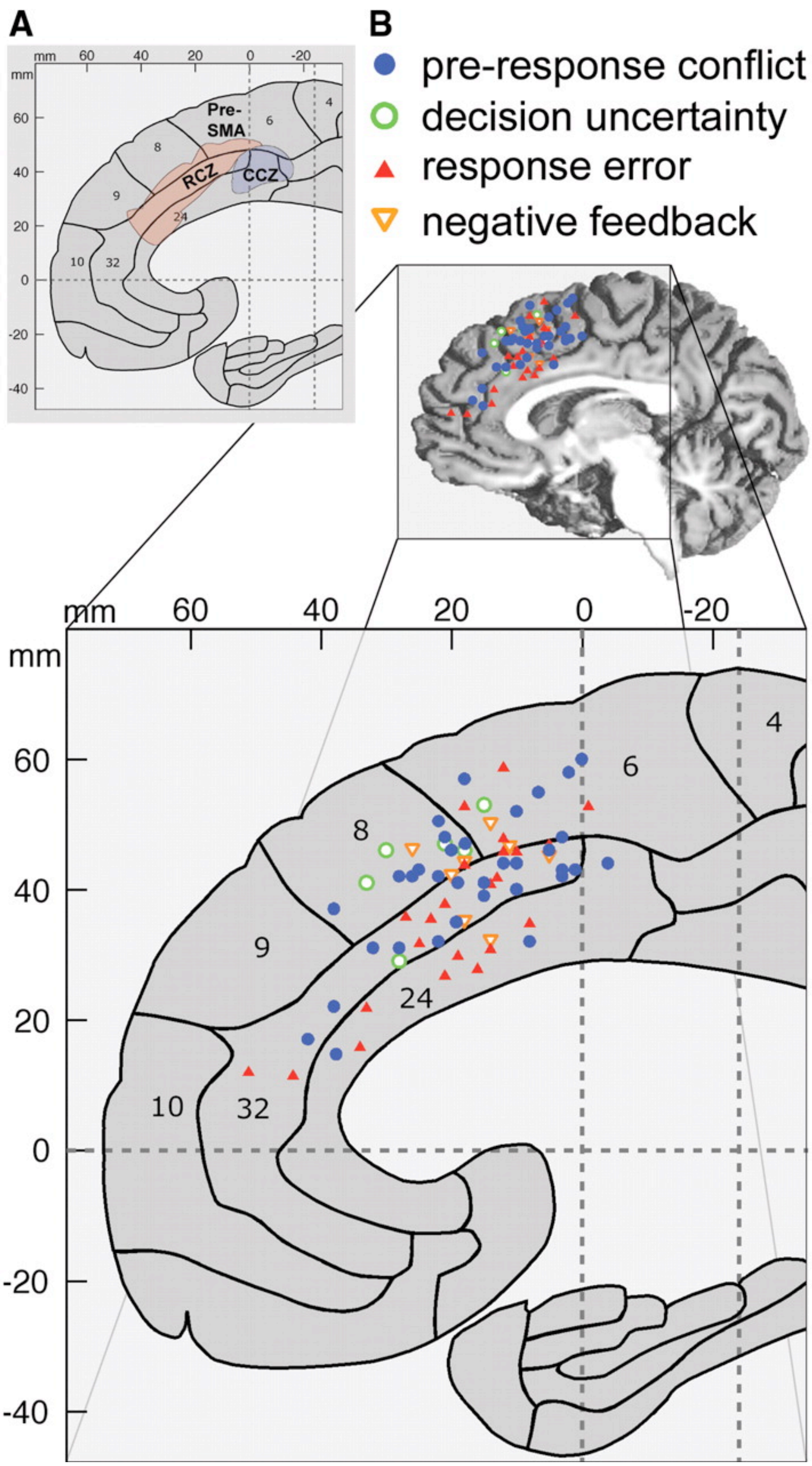
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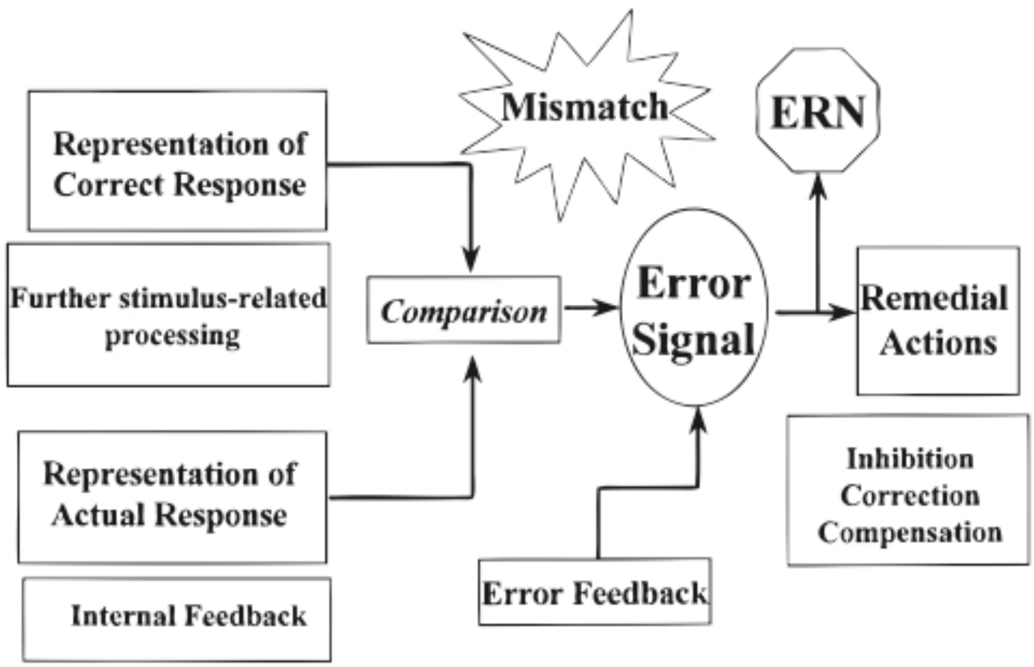
Representation of Correct Response
Further stimulus-related processing
Representation of Actual Response
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Mismatch
Comparison
Error Signal
Error Feedback
ERN
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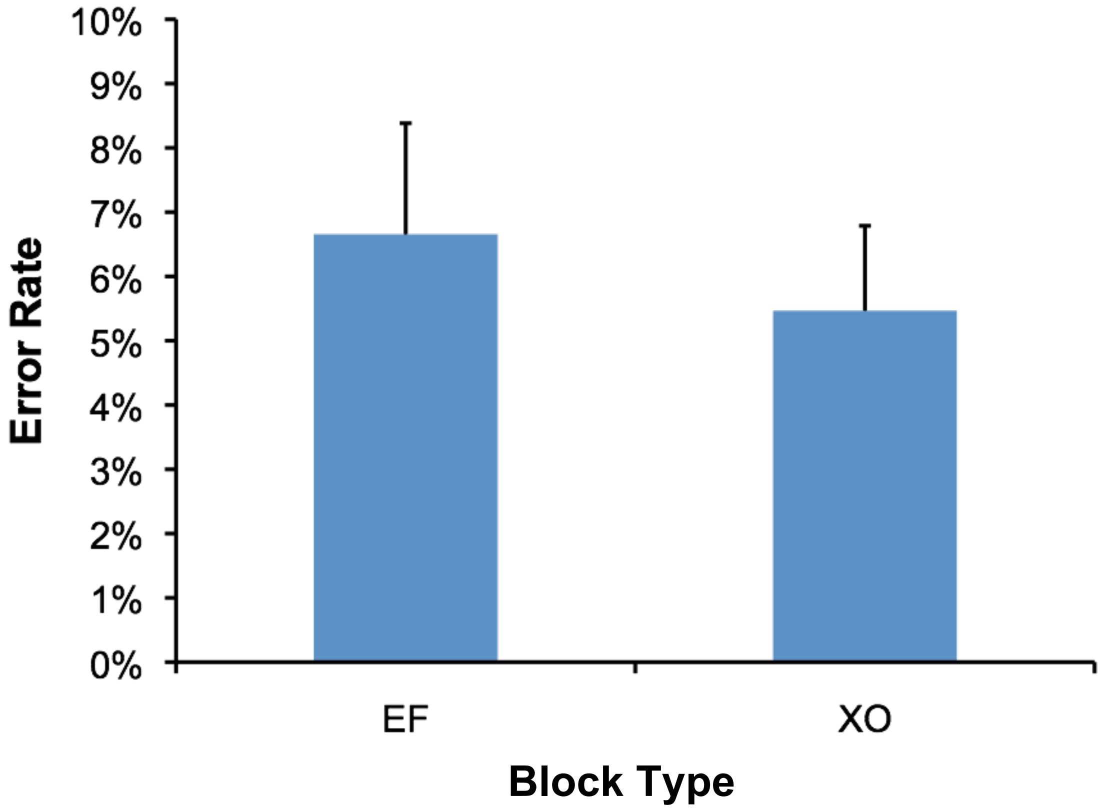
Correction
Compensation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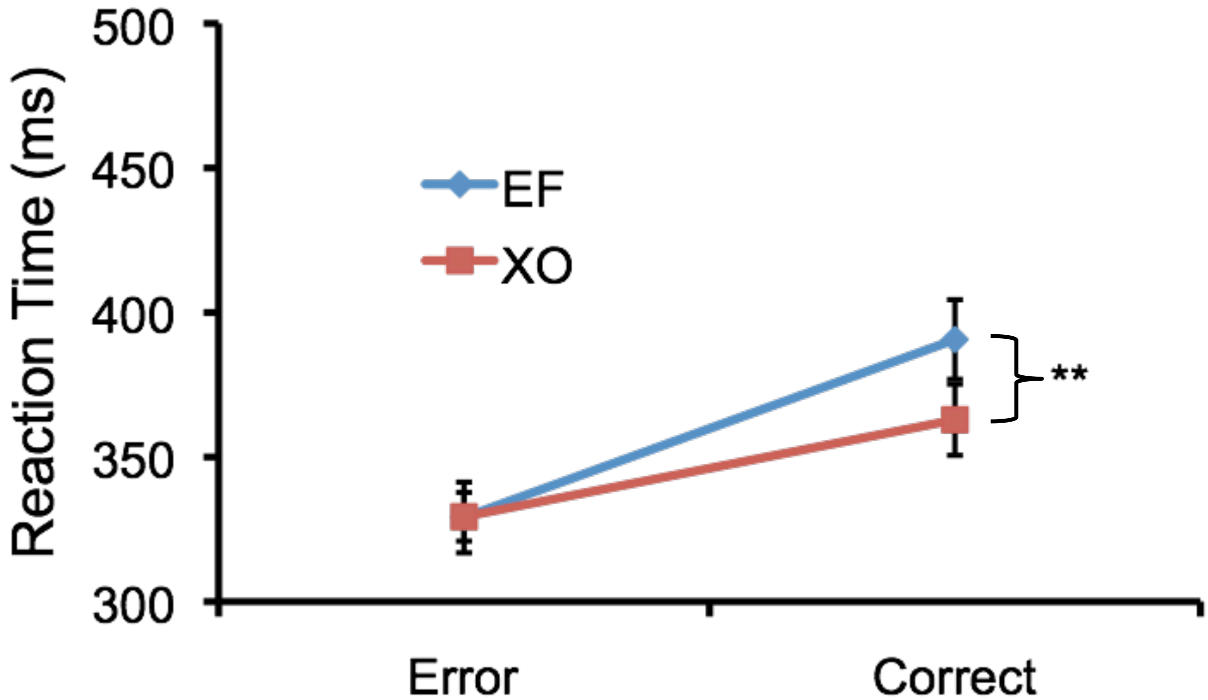
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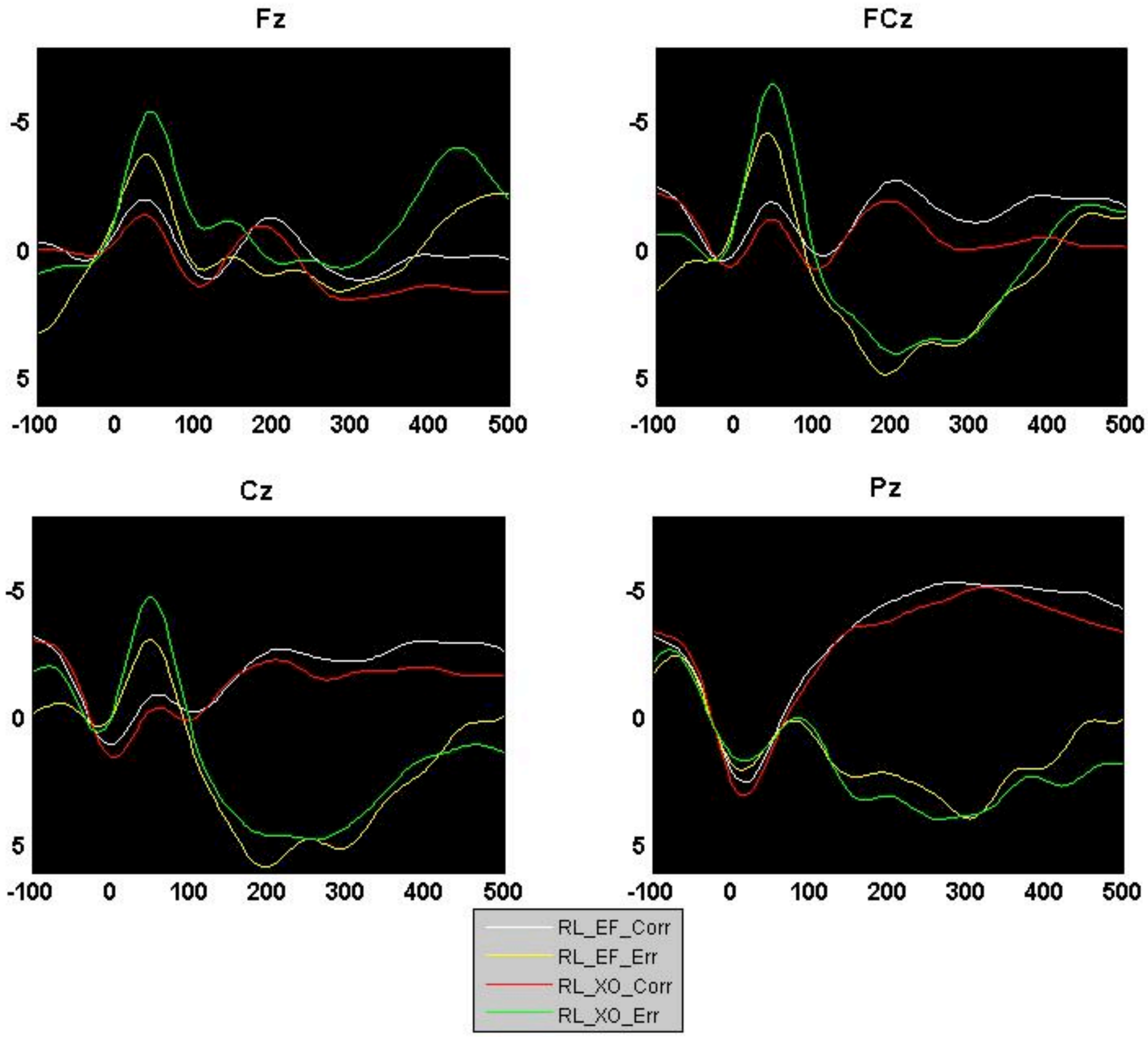
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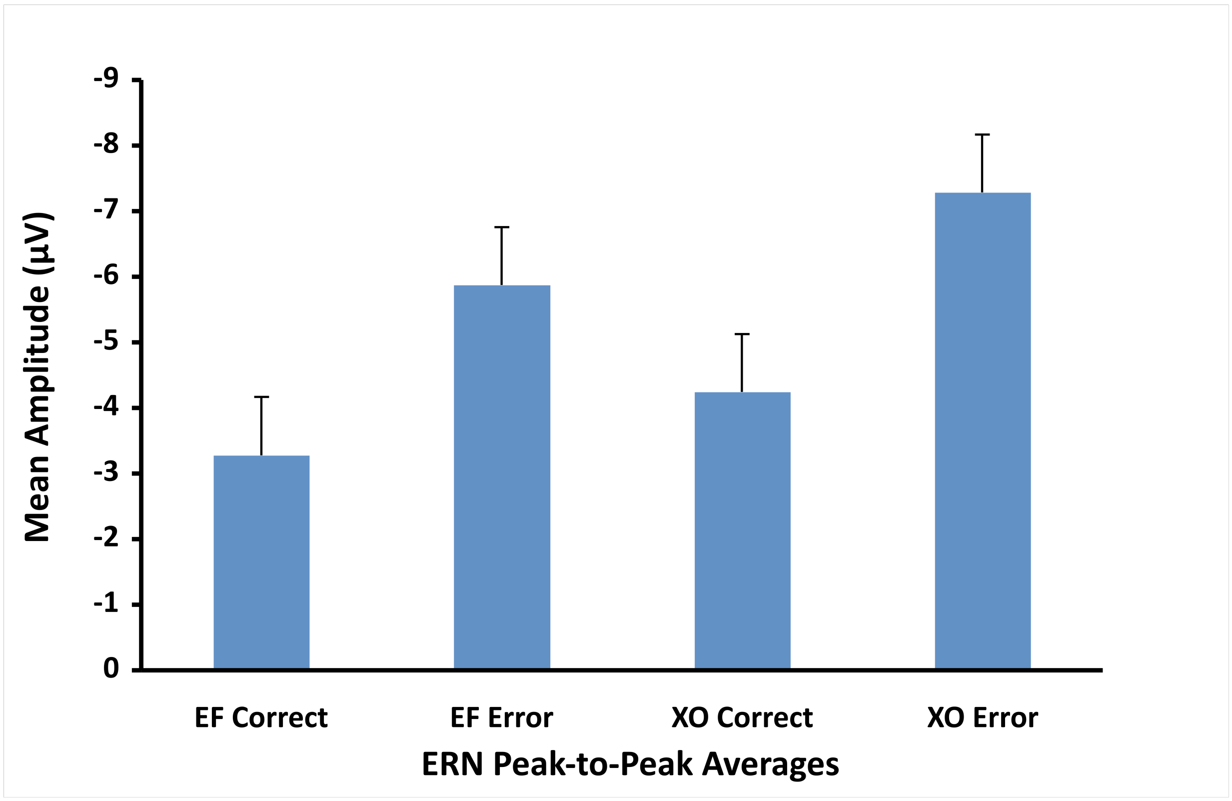
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Mean Amplitude (µV)
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EF Error
XO Correct
XO Error
ERN Peak-to-Peak Averages